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Control of bubble size and bubble number in bubble electrospinning

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ABSTRACT

The surface tension of a bubble depends upon its size; a smaller bubble requires a smaller electronic force for fabrication of ultrafine fibers using bubble electrospinning. The electronic field triggers rupture of interacted bubbles to form daughter bubble cascades, so a very low voltage is needed for nanofiber fabrication.

1. Introduction

Polymer bubbles are widely used for fabrication of ultrafine fibers [1–4] because of their excellent property that the surface tension of a bubble depends upon its size.

Consider a bubble; its surface tension σ can be expressed in the form [2]

$$\sigma = \frac{1}{4} r (P_i - P_o) \tag{1}$$

where P_i and P_o are the air pressures inside and outside the bubble respectively, and r is its radius.

For a nanobubble, it requires a very small force to overcome the surface tension. So far we have produced nanofibers with diameters of about 20 nm [5] using bubble electrospinning.

During the bubble electrospinning, it is very difficult to control the bubble's size and bubble number on a surface of a polymer solution. In this paper we will study the interaction of bubbles under an electronic field, and the bubble number during bubble electrospinning.

2. Bubble interaction under an electronic field

The bubble electrospinning setup [2] consists of a vertical solution reservoir with a gas tube feeding from the bottom, in which there is a metal electrode fixed along the centerline of the tube, and a grounded collector over the reservoir. It has been found that many small bubbles with different sizes were produced on the solution surface. The mechanism of the new electrospinning process is deceptively simple: in the absence of an electric field, the aerated solution forms various bubbles on the surface. When an electric field is present, it induces charges in the bubble surface; these quickly relax to the bubble surface. The coupling of surface charge and the external electric field creates a tangential stress, resulting in the deformation of the small bubble into a protuberance-induced upward-directed reentrant jet. Once the electric field exceeds the critical value needed to overcome the surface tension, the bubble is broken, and the curved film of the ruptured bubble can fold and entrap air as it retracts; as a result, numerous smaller daughter bubbles are formed [6,7], which are then further pulled

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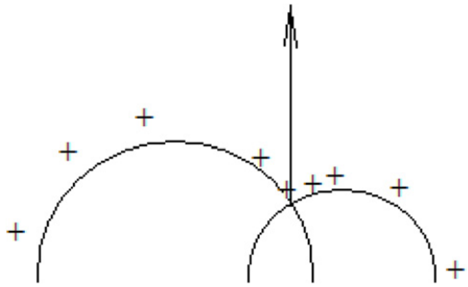

Fig. 1. The interaction of two bubbles under an electronic field.

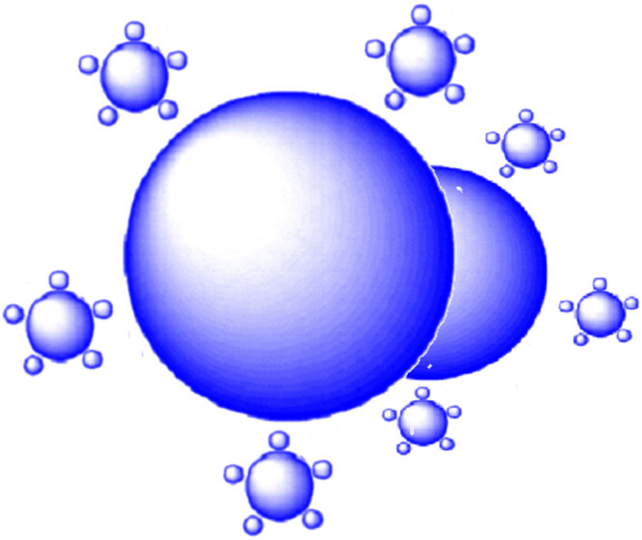

Fig. 2. Daughter bubble cascades formed when two interacted bubbles rupture.

upwards by the electrostatic force, and the daughter bubbles are broken again to form sub-daughter bubble cascades. The process can continue until the sub-daughter bubbles are ejected into the metal receiver as multiple charged jets.

Generally multiple bubbles with various different sizes on the bubble surface are produced during the bubble electrospinning. When two bubbles meet together, they will merge walls to minimize their surface area, and the surface charges of both merged parts of the surfaces will move to a common wall; see Fig. 1. Before the smaller bubble bulges into the larger bubble, the electronic force pulls the common wall upwards, making both bubbles break, and smaller daughter bubbles are formed around the broken bubbles; see Fig. 2. The daughter bubbles will interact with other bubbles, and sub-daughter bubbles are formed when a daughter bubble is broken. The process continues until some hierarchical ruptured bubble is pulled upwards to form a charged jet, which is then received on the metal receiver as nanofibers. This event typically occurs within milliseconds, and thousands of charged jets are pulled upwards to the metal receiver above.

3. Bubble number

Bubble number in daughter bubble cascades directly affects the throughput of nanofibers. A big bubble with radius r, under interaction with a small bubble, will be ruptured into daughter bubble cascades. By the assumption of the conservation of the total surface area of daughter bubble cascades, we have

$$2\pi r^2 = N \cdot 2\pi r_1^2 = N^2 \cdot 2\pi r_2^2 = \cdots = N^n \cdot 2\pi r_n^2 \tag{2}$$

or

$$r_n = \frac{r}{N^{n/2}} \tag{3}$$

where N is the daughter bubble number, and r_n is the radius of the nth sub-daughter bubble. Assuming $r = 20$ mm, $r_n = 20$ nm and $N = 6$, from Eq. (3) we have $n = 15$; that means that the number of bubbles can be as much as

$$N^n = 4.7 \times 10^{11}. \tag{4}$$

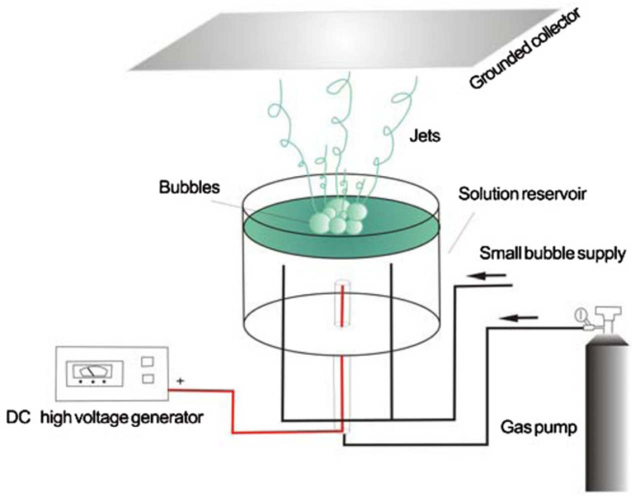

Fig. 3. Small bubble supply in the bubble electrospinning.

The surface tension of a sub-daughter bubble can be expressed in the form

$$\sigma_n = \frac{1}{4} r_n (\Delta P)_n \tag{5}$$

where $(\Delta P)_n$ is the air pressure difference between the inside and outside of the sub-daughter bubble. The pressure of the inner entrapped air of a sub-daughter bubble is very close to the pressure outside; that means that $(\Delta P)_n < (\Delta P)_{n-1}$. The surface tension of a sub-daughter bubble reduces remarkably. During the bubble electrospinning, it is, therefore, very important to trigger big bubbles to form daughter bubble cascades. To this end, a small bubble supply is added to a classical bubble electrospinning; see Fig. 3.

4. Conclusion

The electronic field in bubble electrospinning causes a high charge density on the common walls of interacted bubbles, triggering bubble rupture to form daughter bubble cascades. The size and number of sub-daughter bubbles mainly depends upon the applied voltage and the initial size of interacted bubbles. The process with a small bubble supply requires a minimal energy consumption, and the bubble spinning offers a more challenging opportunity for mass production of nanofibers.

Acknowledgments

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References

[1] Y. Liu, J.H. He, Bubble electrospinning for mass production of nanofibers, Int. J. Nonlinear Sci. Numer. Simul. 8 (2007) 393–396. 7.
[2] J.H. He, Y. Liu, L. Xu, BioMimic fabrication of electrospun nanofibers with high-throughput, Chaos Solitons Fractals 37 (2008) 643–651.
[3] R.R. Yang, J.H. He, L. Xu, et al., Bubble-electrospinning for fabricating nanofibers, Polymer 50 (24) (2009) 5846–5850.
[4] Z.F. Ren, J.H. He, Single polymeric bubble for the preparation of multiple micro/nano fibers, J. Appl. Polym. Sci. 119 (2011) 1161–1165.
[5] R.R. Yang, J.H. He, J.Y. Yu, Bubble-electrospinning for fabrication of nanofibers with diameter of about 20 nm, Int. J. Nonlinear Sci. Numer. Simul. 11 (S) (2010) 163–164.
[6] J.C. Bird, R. de Ruiter, L. Courbin, et al., Daughter bubble cascades produced by folding of ruptured thin films, Nature 465 (2010) 759–762.
[7] J.H. He, Effect of temperature on surface tension of a bubble and hierarchical ruptured bubbles for nanofiber fabrication, Thermal Science 16 (1) (2012) 325–328.